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DYNAMIC STABILITY CHARACTERISTICS
OF A 10-DEG CONE AT MACH NUMBER 20

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ARO, Inc.

and

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Aerospace Research Laboratories
Office of Aerospace Research
United States Air Force

April 1965

VON KÁRMÁN GAS DYNAMICS FACILITY

ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was completed at the request of Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC) under Program Element 65402034.

The results of tests presented were jointly obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1000 and the Fluid Dynamic Facilities Laboratory, Aerospace Research Laboratories (ARL), Office of Aerospace Research (OAS), Wright-Patterson Air Force Base (WPAFB), Ohio. The tests were conducted during September and December, 1964 at ARL under ARO Project No. VT3116, and the report was submitted by the authors on March 26, 1965.

Appreciation must be extended to N. E. Scaggs and the many other personnel of the ARL for their effort and cooperation in making the test effort a success.

This technical report has been reviewed and is approved.

Darreld K. Calkins   Jean A. Jack
Major, USAF   Colonel, USAF
AF Representative, VKF   DCS/Test
DCS/Test

ABSTRACT

Tests were conducted in the 30-Inch Hypersonic Tunnel on the Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio to determine the effects of Reynolds number and frequency of oscillation on the damping-in-pitch derivatives of a 10-deg half-angle cone. Free oscillation data were obtained at a nominal Mach number of 20, at Reynolds numbers, based on model base diameter, from 50,000 to 100,000, and at model oscillation frequencies from 8 to 45 cps. Test results are presented, and comparisons are made with modified Newtonian impact theory and an unsteady flow field theory.

CONTENTS

ILLUSTRATIONS

TABLE

NOMENCLATURE

A	Reference area (base area), ft^2
C_m	Pitching-moment coefficient, pitching moment/$q_\infty Ad$
C_{m_q}	$\left[\partial C_m / \partial(qd/2V_\infty)\right]$ $q \longrightarrow 0$
$C_{m_{\dot\alpha}}$	$\left[\partial C_m / \partial(\dot\alpha d/2V_\infty)\right]$ $\dot\alpha \longrightarrow 0$ Damping-in-pitch derivatives, 1/rad
C_{y_R}	Number of cycles to damp to a given amplitude ratio, R, cycles
d	Reference length (model base diameter), ft
f	Frequency of oscillation, cps
I	Model and flexure moment of inertia about pivot axis, slugs-ft^2
M_θ	Angular restoring-moment parameter, ft-lb/rad
$M_{\dot\theta}$	Angular viscous-damping parameter, ft-lb-sec/rad
$M'_{\dot\theta}$	Aerodynamic angular viscous-damping-moment parameter, ft-lb-sec/rad
M_∞	Mach number
p_0	Stilling chamber total pressure, psia
q	Pitching velocity, rad/sec
q_∞	Free-stream dynamic pressure, psf
R	Ratio of amplitude of a damped oscillation after a number of cycles to the initial amplitude
Re_d	Reynolds number based on model base diameter
T_0	Stilling chamber total temperature, °R
t	Time, sec
V_∞	Free-stream velocity, fps
$\dot\alpha$	Time rate of change of angle of attack, rad/sec
θ	Angular displacement, rad or deg
$\dot\theta$	Angular velocity, rad/sec
$\ddot\theta$	Angular acceleration, rad/sec^2
ω	Angular frequency, $2\pi f$, rad/sec

$\dfrac{\omega d}{2V_\infty}$ Reduced frequency parameter, rad

SUBSCRIPTS

o   Maximum conditions

v   Vacuum conditions

w   Wind-on conditions

SECTION I
INTRODUCTION

When an aerodynamic model is tested in a wind tunnel, it is desirable to duplicate the Reynolds number and the Mach number of its full-scale counterpart assuming real gas effects are not of interest. If the body is a dynamic model, then the model should be tested at the same reduced frequency as the full-scale vehicle.

The only wind tunnel facilities that are available at the von Kármán Gas Dynamics Facility (VKF), AEDC for testing at M_∞ = 20 are hotshot tunnels which are short run time (50 msec useful run duration) facilities which require that the model oscillation frequency be very high (~150 cps) in order to obtain dynamic stability data. The flow velocity in the hotshot facility is about 10,000 ft/sec. Because of the low velocity and high frequency, compared to flight, the reduced frequencies available in these tunnels are on the order of 30 times higher than those in flight. In order to establish the role of the reduced frequency (frequency of oscillation) in dynamic stability testing in the hotshot tunnels, it would be necessary to compare the data from the hotshot facilities with the data obtained in long run time facilities where full-scale reduced frequencies may be duplicated.

A program was initiated to conduct dynamic stability tests at the Fluid Dynamics Facilities Laboratory (ARF), Aerospace Research Laboratories (ARL), Office of Aerospace Research (OAS), Wright-Patterson Air Force Base (WPAFB), Ohio, where wind tunnel facilities capable of useful run times of up to 2 min are available. The tests were conducted in the ARL 30-Inch Hypersonic Wind Tunnel using a free oscillation, low amplitude (±1.5 deg) dynamic stability balance. Experimental data presented in this report were obtained at a nominal Mach number of 20, at zero angle of attack, for Reynolds numbers ranging from 50,000 to 100,000 and at reduced frequencies ranging from 0.0019 to 0.0107 rad. Comparisons are made between these experimental results and modified Newtonian impact theory and an unsteady flow field theory.

SECTION II
APPARATUS

2.1 WIND TUNNEL

The ARL 30-Inch Hypersonic Wind Tunnel, shown schematically in Fig. 1 and fully described in Ref. 1, is a free-jet facility that is operated

in a blow-down fashion using axisymmetric nozzles to generate high Mach number airflows. This facility is operated at Mach numbers from 16 to 22 and with Reynolds numbers from 10^4/ft to 10^5/ft at air reservoir temperatures to 4000°R. Presently the facility is operated at temperatures only slightly above the experimental condensation curve for hypersonic facilities (Ref. 2). A 3000-psia high pressure air storage station and a 135,000-cu-ft vacuum sphere system coupled to a three-stage vacuum pumping station provide the required pressure ratio for establishment of flow. Storage air is processed with silica-gel dryers to a dew-point below -60°F at atmospheric pressure. The heater for the tunnel is a gas-fired, ceramic pebble bed, regeneration-type storage heater. In operation, the 12.5-ft-deep bed of 7/8-in.-diam pebbles is heated by a methane-oxygen air burner.

The facility is presently equipped with a conical nozzle having interchangeable throat sections and a 30-in. exit diameter. The nozzle enters into a 5-ft cubic test cabin. The dimensions of the test cabin allow sufficient room for installation and storage of instrumentation and/or models outside the test jet.

The facility is currently operating with test run times on the order of 2 min with an established hypersonic isentropic jet (test core) of about 20-in. diameter.

2.2 BALANCE

The balance is a remotely controlled, pneumatically operated, sting-supported, free oscillation, low amplitude (±2 deg), one-degree-of-freedom system (Fig. 2). The pivots used in these tests were two sets of cross flexures with nominal stiffnesses of 58 and 680 ft-lb/rad.

The model pivot system is pneumatically displaced to a desired amplitude by a set of displacement arms which apply a couple about the pivot axis of the balance. Once the desired amplitude is reached, the pneumatically operated releasing piston (Fig. 2) is fired into the set of cams which made contact with the set screws located in the displacement arms, thereby releasing the static couple.

Because of the high stagnation temperatures encountered during the operation of the tunnel, a portion of the balance was water cooled by means of wrapping copper tubing around the rear portion of the balance and internally cooled by air directed on the model bulkhead. External model cooling was provided, when data were not being taken, by a retractable air cooling device (Fig. 3). Essentially the external cooling device

consisted of nine orifices arranged in a cruciform to provide a uniform airflow along the models periphery.

The time history of the motion of the models was measured with a direct-writing oscillograph in conjunction with a strain-gage bridge mounted on one of the cross flexures.

2.3 MODELS

The models were conical bodies of revolution having 10-deg semi-vertex angles, bluntness ratios (nose to base radius) of 0.017, and pivot axes locations of 58.7 percent of the model length (Fig. 4). The models were fabricated from 303 stainless steel. Two nose sections were fabricated, one solid and the other hollow. These nose sections in combination with an aft ballast weight enabled the tests to be performed on models of two different inertias. The combination of two pivots and two model inertias yielded four dynamic models whose frequencies of oscillation were 8.1, 12.6, 28.8, and 44.9 cps.

SECTION III
PROCEDURE

3.1 DATA REDUCTION

The equations of motion for a free oscillation, one-degree-of-freedom system may be expressed as

$$I\ddot{\theta} - M_{\dot{\theta}}\dot{\theta} - M_{\theta}\theta = 0.$$

The method for computing the dimensionless damping-in-pitch derivatives is indicated by the following expressions:

$$\theta = \theta_o e^{(M_{\dot{\theta}}/2I)t} \sin \sqrt{-M_{\theta}/I} \, t$$

$$M_{\dot{\theta}} = \frac{2 \, I \, \ln \, R}{C \, \Upsilon_R}$$

$$M'_{\dot{\theta}} = M_{\dot{\theta}_w} - M_{\dot{\theta}_v} \, (\omega_v/\omega_w)$$

$$C_{m_q} + C_{m_{\dot{\alpha}}} = M'_{\dot{\theta}} \, (2 \, V_\infty/q_\infty \, A d^2)$$

3

The expression for obtaining the aerodynamic viscous-damping parameter ($M'_{\dot\theta}$) is based on the premise that the structural damping of a cross-flexure pivot varies inversely with the frequency of oscillation (Ref. 3).

Correction factors, to account for the variation of the ratio of specific heats, as a function of stagnation pressure and temperature were obtained empirically from flow calculations based on the Beattie-Bridgeman equation of state, (Refs. 4 and 5). These factors were applied to the isentropic flow relationships to obtain V_∞, q_∞, and Re_d.

3.2 TESTS

The wind-on damping measurements and the damping measurements with wind-off, at atmospheric conditions, were conducted at ARL. The wind-off damping measurements at near vacuum conditions (typically 10 microns) were conducted at the VKF and evaluated for all four models at the same mean amplitudes.

The wind-on test procedure consisted of cooling the model balance system until the steady-state tunnel conditions had been established. Cooling was then discontinued, and the model was displaced and released with the resulting motion recorded on a direct-writing oscillograph. The tests were conducted at $M_\infty = 20$, zero angle of attack, and mean amplitudes of ±1.5 deg, for Reynolds numbers ranging from 50,000 to 100,000 and reduced frequencies from 0.0019 to 0.0107 rad. A summary of the test conditions is presented in Table I.

SECTION IV
PRECISION OF MEASUREMENTS

The measurement of the damping-in-pitch derivatives is affected by the uncertainties in determining the model moment of inertia (I), the angular frequency of oscillation (ω), and the amplitude ratio (R).

As a result of the above sources of error, the maximum estimated uncertainty in measuring the damping-in-pitch derivatives, $C_{m_q} + C_{m_{\dot\alpha}}$, is ±0.5.

SECTION V
RESULTS

Figure 5 exhibits the effects of a Reynolds number variation on the damping-in-pitch derivatives for the four models tested. The models having the two lowest reduced frequencies (0.0019 and 0.0030 rad) display the trend of increasing dynamic stability with Reynolds number. The configurations having the two highest reduced frequencies (0.0068 and 0.0107 rad) display the trend of decreasing dynamic stability with increasing Reynolds number.

Figure 6 illustrates the effects of a reduced frequency variation on the damping-in-pitch derivatives for near constant values of Reynolds numbers. At the two lower values of Reynolds numbers (50,000 and 70,000) model dynamic stability is increased as the reduced frequency is increased; whereas at a Reynolds number of approximately 100,000 model damping is unaffected by varying the reduced frequency.

Both unsteady flow field theory (Ref. 6) and modified Newtonian impact theory (Refs. 7 and 8) are conservative in the prediction of the damping-in-pitch derivatives. The low frequency data (Fig. 5) indicate a trend of increasing with Reynolds number and would be expected to approach the theoretical predictions at higher Reynolds numbers where the theory should be more applicable.

SECTION VI
CONCLUSIONS

A wind tunnel test program was conducted in the ARL 30-Inch Hypersonic Tunnel to determine the effects of frequency of oscillation and Reynolds number on the dynamic stability of a 10-deg half-angle cone. Conclusions based on these tests are:

1. Increasing the frequency of oscillation increases the dynamic stability at low Reynolds numbers but does not significantly affect it at high Reynolds numbers.

2. Increasing Reynolds number may dynamically stabilize or destabilize a model, depending on the frequency of oscillation.

3. Both modified Newtonian impact theory and unsteady flow field theory are in poor agreement with these measured data.

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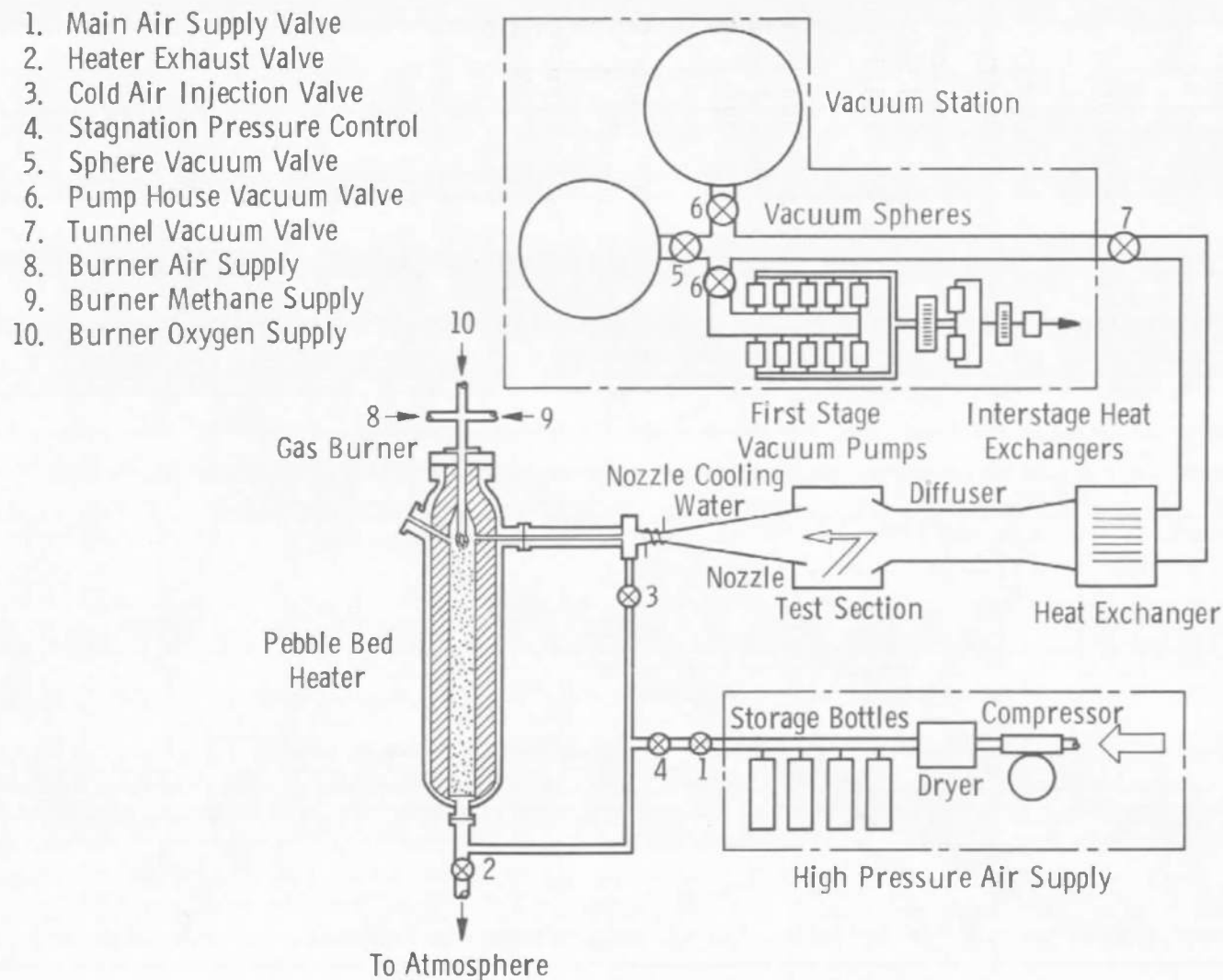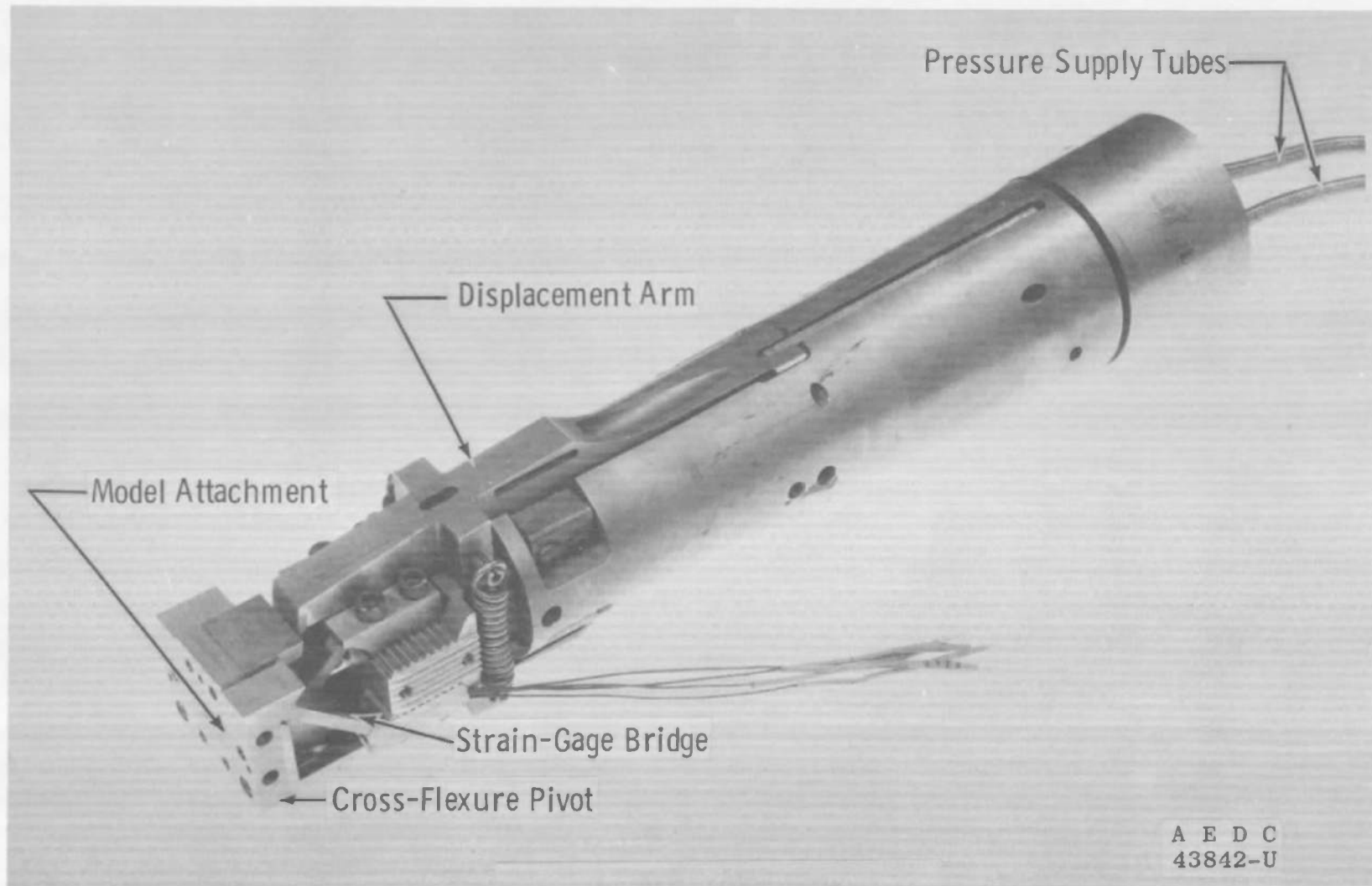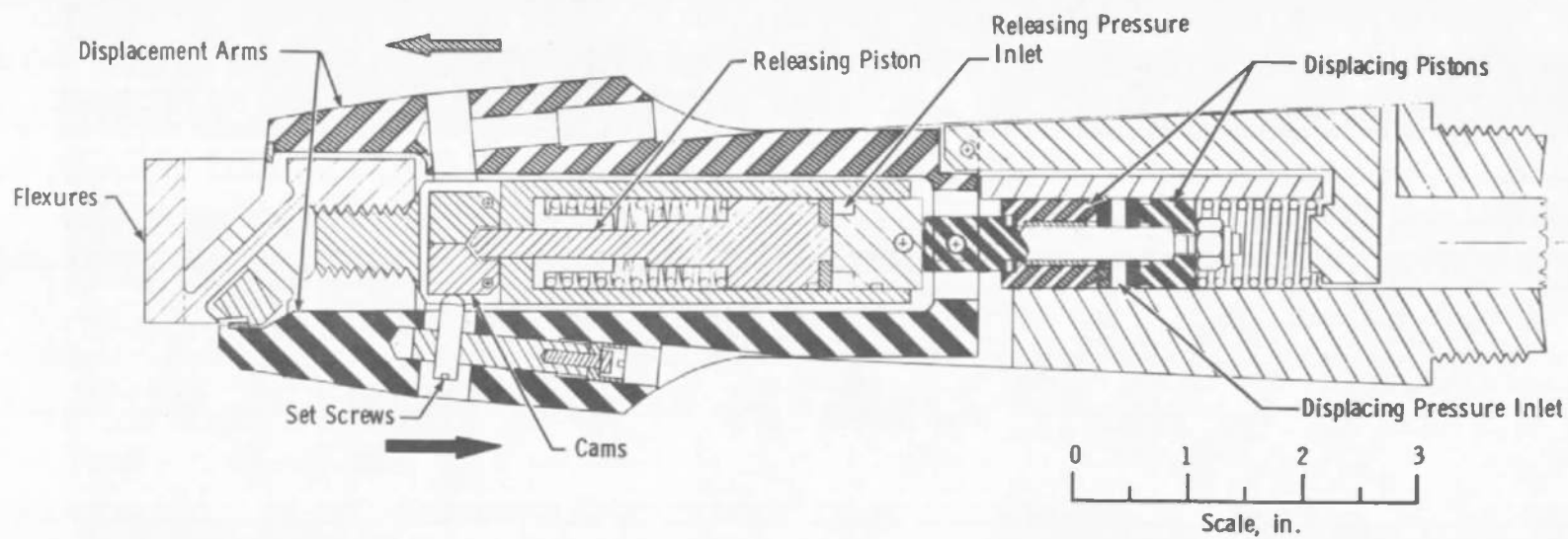
1. Main Air Supply Valve
2. Heater Exhaust Valve
3. Cold Air Injection Valve
4. Stagnation Pressure Control
5. Sphere Vacuum Valve
6. Pump House Vacuum Valve
7. Tunnel Vacuum Valve
8. Burner Air Supply
9. Burner Methane Supply
10. Burner Oxygen Supply

Vacuum Station

Vacuum Spheres

First Stage
Vacuum Pumps

Interstage Heat
Exchangers

Gas Burner

Nozzle Cooling
Water

Diffuser

Nozzle
Test Section

Heat Exchanger

Pebble Bed
Heater

Storage Bottles

Compressor

Dryer

High Pressure Air Supply

To Atmosphere

Fig. 1 Schematic of the ARL 30-Inch Hypersonic Wind Tunnel

Pressure Supply Tubes

Displacement Arm

Model Attachment

Strain-Gage Bridge

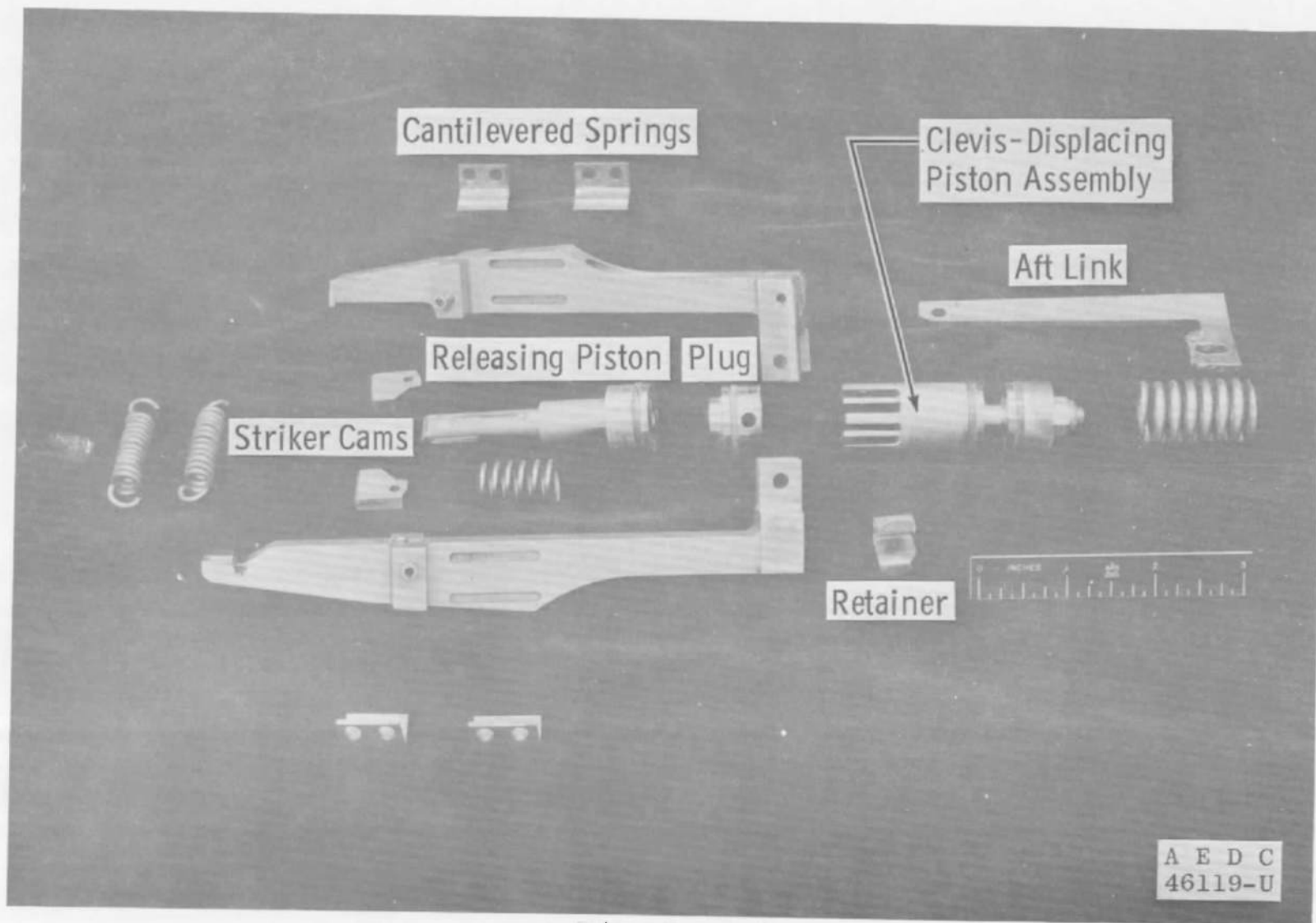Cross-Flexure Pivot

A E D C
43842-U

a. Assembled View

Fig. 2 Dynamic Stability Balance

b. Sectional View

Fig. 2 Continued

c. Balance Components
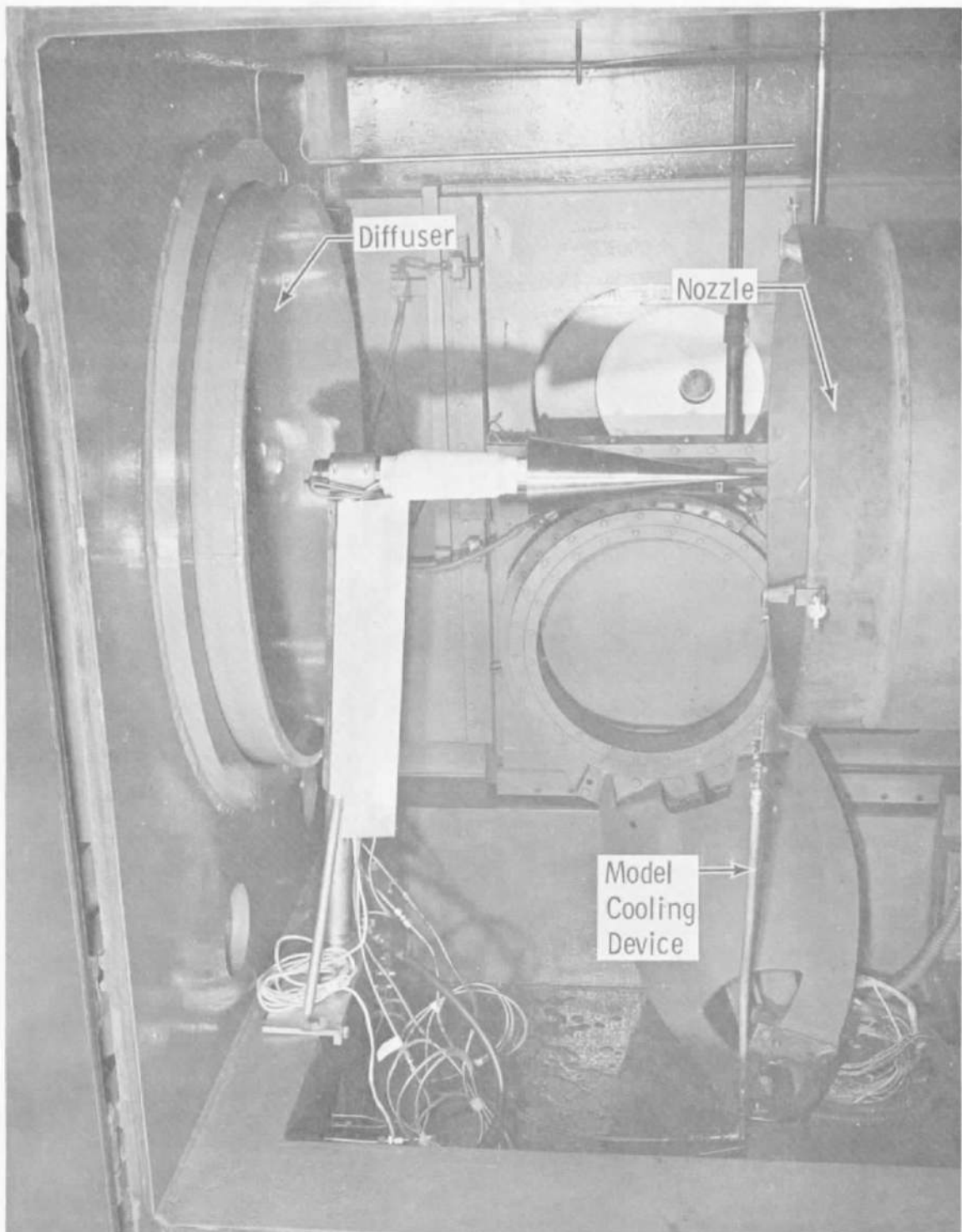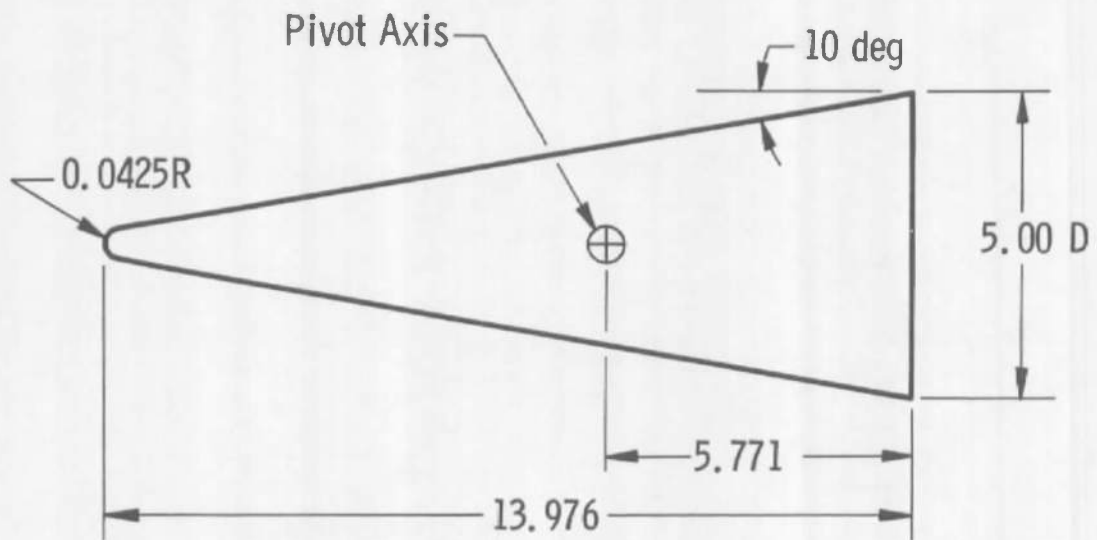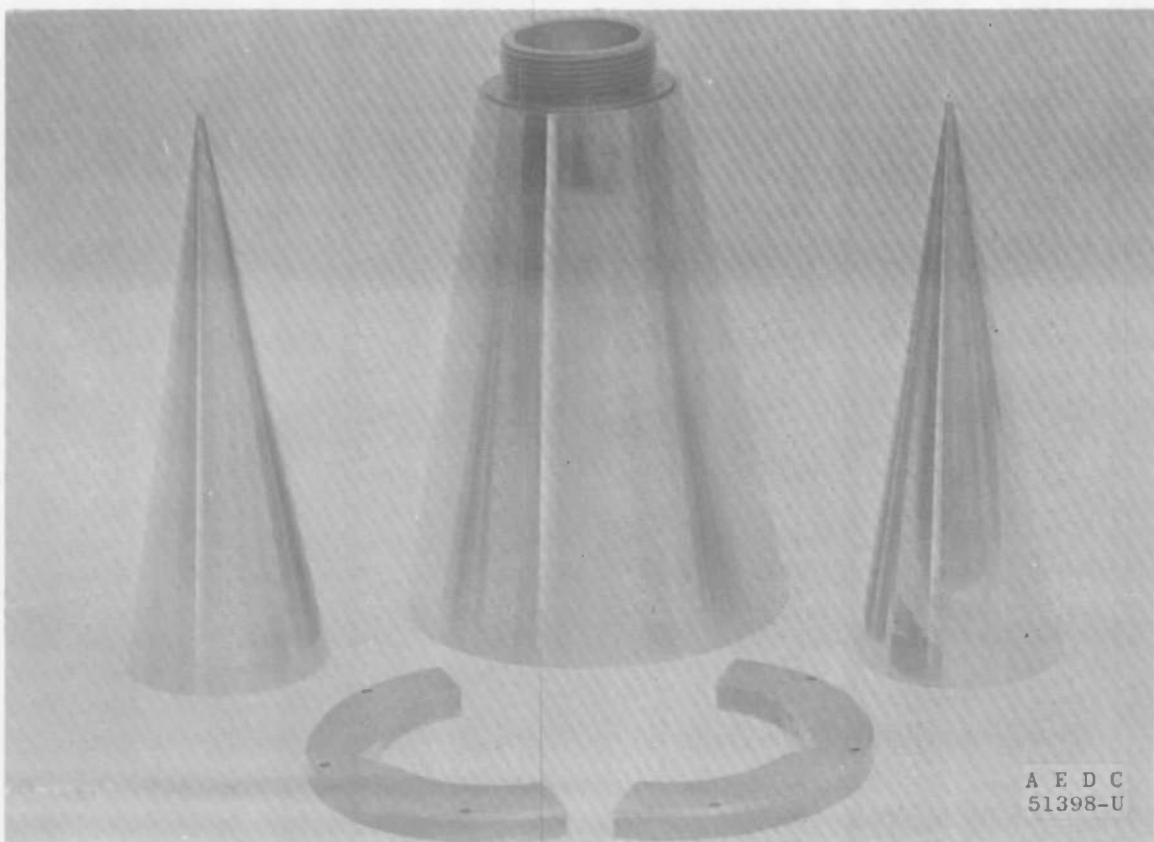
Fig. 2 Concluded

Fig. 3 Model-Balance Installed in Test Cabin

All dimensions are in inches.

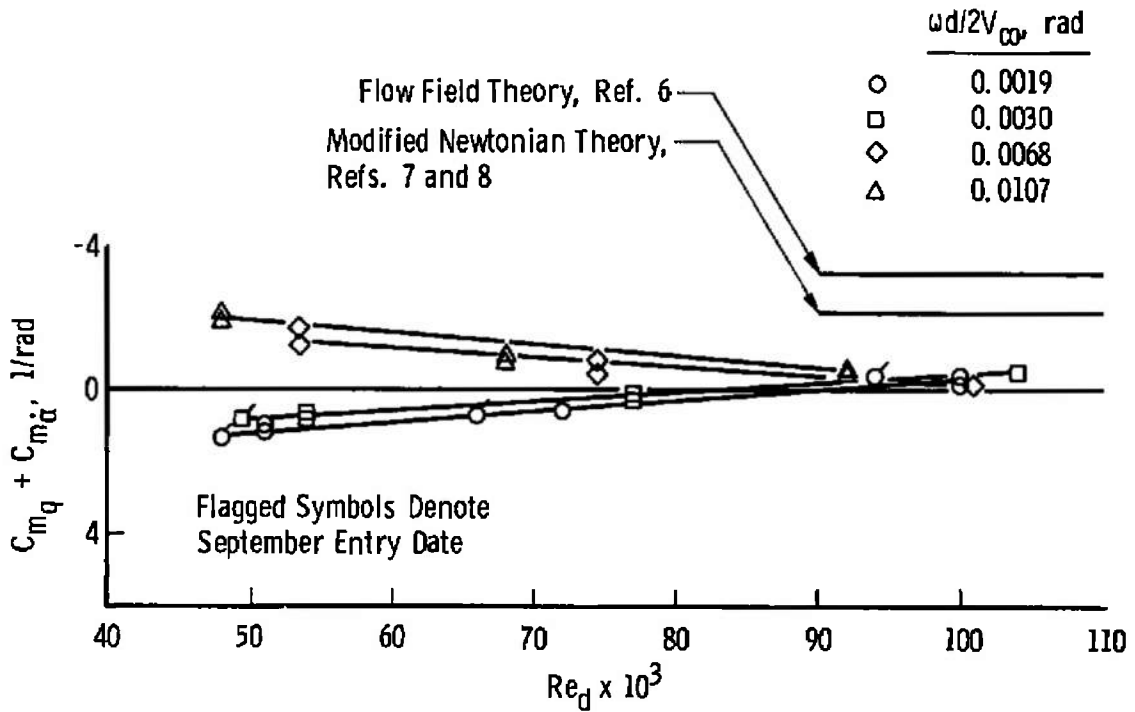a. Geometry

b. Photograph

Fig. 4 Wind Tunnel Model

Fig. 5 Damping-in-Pitch Derivatives versus Reynolds Number

Fig. 6 Damping-in-Pitch Derivatives versus Reduced Frequency Parameter

TABLE I
TEST SUMMARY

Entry	M_∞	T_O, °R	p_O, psi	V_∞, fps	θ, deg	f, cps	$\omega d/2V_\infty$, rad	Re_d
Sept. 64	20	2300 → 2400	1000 → 2000	5400	11.5	8.1	0.0019	48,000 → 94,000
						12.6	0.0030	49,000
Dec. 64						8.1	0.0019	51,000 → 100,000
						12.6	0.0030	54,000 → 104,000
						28.8	0.0068	54,000 → 101,000
						44.9	0.0107	48,000 → 92,000

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13 ABSTRACT

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